Relevant changes in revised manuscript

The main changes are summarized in this overview. More detailed changes can be found from the mark-up version below.

The manuscript has been shortened from 33 page to 29 page, with more than 1800 words less in current version.

A new figure of model-data comparison has been included. Meanwhile, three more figures have been moved to the online supplementary material to save the space.

Effects of melting ice sheets and orbital forcing on the early Holocene warming in the extratropical Northern Hemisphere

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Abstract

The early Holocene is ~~a critical period for climate change, as it~~ marked by the final transition from the last deglaciation to the relatively warm~~ and stable~~ Holocene.~~ It is characterized by a warming trend that has been registered in numerous proxy records. This climatic warming was accompanied by major adjustments in different climate components, including the decaying of ice sheets in cryosphere, the perturbation of circulation in the ocean, the expansion of vegetation (over the high latitude) in biosphere.~~ ~~Previous s~~Studies have analyzed the influence of the demise of the ice sheets and other forcings on the climate system during the Holocene. ~~However, t~~The climate response to the forcings ~~together with the internal feedbacks~~ before 9 ka, however, remains not fully comprehended. ~~In this study, w~~We therefore disentangle how ~~the~~orbital and ice-sheet forcings contributed to climate change during the earliest part of the Holocene (11.5–7 ka) by employing the LOVECLIM climate model~~ for both equilibrium and transient experiments~~.

~~The results of o~~Our equilibrium experiments for 11.5 ka ~~reveal thatthe~~suggest a lower annual mean temperature at the onset of the Holocene ~~was lower~~ than in the preindustrial era in the Northern extratropics with the ~~,~~exception of ~~in~~ Alaska. The magnitude of this cool anomaly varies regionally and these spatial patterns is broadly consistent with proxy-based.~~ as a response to varying climate forcings and diverse mechanisms. In eastern N America and NW Europe~~, ~~the temperatures~~ Temperatures throughout the whole year in N Canada and NW Europe for 11.5 ka were 2–5~~-~~°C lower than in the preindustrial ~~control,~~era ~~reaching the maximum cooling~~ as ~~here~~ the climate was strongly influenced by the cooling effects of the ice sheets~~.~~, which ~~This cooling of the ice-sheet surface~~ was caused~~ both~~ by ~~the~~ enhanced surface albedo and ~~by the~~ ice sheet orography~~ of the ice sheets~~. ~~For Siberia, a small deviation (-0.5–1.5 °C) in summer temperature and 0.5–1.5 °C cooler annual climate compared to the preindustrial run were caused by the counteraction of the high~~

~~albedo associated with the tundra vegetation which was more southward extended at 11.5 ka than in the preindustrial period and the orbitally induced radiation anomalies. In the eastern part of the Arctic Ocean (over Barents Sea, Kara Sea and Laptev Sea), the annual mean temperature was 0.5–2 °C lower than at 0 ka, because the cooling effect of a reduced northward heat transport induced by the weakened ocean circulation overwhelmed the orbitally induced warming. The 0.5–3 °C cooler climate over the N Labrador Sea and N Atlantic Ocean was related to the reduced northward heat transport and sea-ice feedbacks initiated by the weakened ocean circulation.~~ In contrast, temperatures in Alaska~~, temperatures in~~ for all seasons were 0.5–3~~-~~°C higher than the control ~~run~~ run, which were caused by a combination of ~~primarily due to the~~ orbital forcing and ~~ly induced positive insolation anomaly and also to the enhanced~~ stronger southerly winds ~~which~~that advected warm air from the South ~~as a~~in response to ~~the~~ prevailing high air pressure over the Laurentide Ice Sheet (LIS).

The~~Our~~ transient experiments indicated ~~that the Holocene temperature evolution, and the~~a highly inhomogeneous early Holocene temperature~~warming~~ over different regions~~vary between different regions~~. The climate i~~I~~n Alaska~~, the climate is~~ was constantly cooling over the whole Holocene~~, primarily following the decreasing. In contrast, in N Canada~~, whereas there was an overall fast early Holocene warming in N Canada ~~during the early Holocene is faster than in other areas (up to~~by more than 1~~.88~~ °C ka^{-1} ~~in summer)~~ as a consequence of the progressive LIS decay~~ of the LIS, and the warming lasted till about 7 ka when this deglaciation was completed~~. ~~In NW Europe, the Arctic and Siberia, the overall warming rates are intermediate with about 0.3–0.7 °C ka^{-1} in most of seasons (with only exception in Arctic's winter).~~ Simulated temperatures compared with proxy records illustrated uncertainties related to the reconstruction of ice-sheet deglaciation, which can be constrained by applying different freshwater scenarios. O~~verall, o~~ur results demonstrate the ~~spatial~~ variability of the climate during the early Holocene, both in terms of ~~the~~ spatial patterns and temporal evolution~~temperature distribution and warming rates, as the response to varying dominant forcings and diverse mechanisms~~.

1 Introduction

The early Holocene lasted from 11.5 to 7 ka B.P (hereafter noted as ka), and is palaeoclimatologically interesting as it represents the last transition phase from full glacial to interglacial conditions. This period is characterized by a warming trend in the Northern Hemisphere (NH) that has been registered in numerous proxy records and indicated by stacked temperature reconstructions (Shakun et al., 2012). Oxygen isotope measurements from ice cores in Greenland (Dansgaard et al., 1993; ~~GRIP Members 1993;~~ Grootes et al., 1993; Rasmussen et al., 2006; Vinther et al., 2006; 2008) and the Canadian high-Arctic (Koerner & Fisher, 1990) consistently ~~reflect~~ show an increase ~~shift~~ in $\delta^{18}O$ ~~stable isotope~~ by up to 3–5 ‰, which indicates a couple of degrees warming in the climate system (Vinther et al., 2009) ~~during the early Holocene and then stay at a relatively stable level~~. ~~This isotopic shift implies changes in the climate system, for instance a couple of degrees warming from 11.5 to 7 ka B.P (hereafter noted as ka) (Dahl-Jensen et al., 1998; Vinther et al., 2009).~~ Moreover, ~~T~~this early-Holocene warming ~~trend~~ is also registered in biological proxies~~, –~~. F~~f~~or example, a 4–5~~–~~°C warming in western and northern Europe is indicated by chironomids and~~, plant~~ macrofossils data ~~and pollen assemblages~~ obtained from lake sediments (Brooks & Birks, 2000; Brooks et al., 2012; Birks, 2015). In addition, this transition is recorded in many other high-resolution records from further East in Eurasia, ~~for example~~such as in speleothems from China (Yuan et al., 2004; Wang et al., 2005). ~~Apart from these land-based observations, c~~Comparable trends have been~~are~~ identified in marine sediment core data, such as a ~~rise in~~ sea surface temperature (SST) rise ~~during the early Holocene~~ in the N Atlantic reflected by the variation in $\delta^{18}O$ ~~values~~ and ~~in abundance of~~ planktonic foraminifera (Bond et al., 1993; Kandiano et al., 2004; Hald et al., 2007). ~~Overall, proxy temperature stacks reveal a 3 °C warming in Northern Hemisphere in the early Holocene (Shakun et al., 2012).~~ Although these proxy records provide a general view of early Holocene warming, ~~its~~ their detailed expression in different regions, and the reasons for this spatial variation~~s~~, are poorly known.

~~It is well accepted that t~~The orbitally induced increase in N~~orthern~~ H~~emisphere~~ summer insolation was one of the main external drivers of the climate change during the last deglaciation (Berger, 1988; Denton et al., 2010; Abe-Ouchi et al., 2013; Buizert et al., 2014). This increase peaked in the earliest Holocene ~~at 11 ka. For instance, at 60 °N June insolation at 11 ka was 47 Wm^{-2} above the present-day value~~ (Berger, 1978) and resulted in warming over large areas. ~~In addition to this external orbital forcing, –~~ However, the early Holocene was also characterized by critical adjustments in components of the climate system~~components (e.g., in cryoshere, ocean and biosphere)~~ that further affected the temperature through various feedback~~s~~ mechanisms. In the cryosphere, the Laurentide ice Sheet (LIS) and Fennoscandian Ice Sheet (FIS) were melting at a fast rate and eventually demised around 6.8 ka and 10 ka, respectively (Dyke et al., 2003; Occhietti et al., 2011), which exerted multiple influences on the climate system (Renssen et al., 2009). First, the surface albedo was much higher over the ice sheets compared to those of ice-free surfaces, which resulted in relatively low temperatures. Second, the ice sheet topography can also influence the climate through the mechanism of adjustment to the atmospheric circulation (Felzer et al., 1996; Justino & Peltier, 2005; Langen & Vinther, 2009). For instance, the orography of a large scale ice sheet generated a glacial anticyclone that locally tended to reduced further the temperature (Felzer et al., 1996), but may also have caused a 2–3°C warming over the North Atlantic under the Last

Glacial Maximum (LGM) (Pausata et al., 2011; Hofer et al., 2012). Third, both modelling and proxy studies have found that the Atlantic Meridional Overturning Circulation (AMOC) was relatively weak during the early Holocene due to the ice sheets melting, which led to reduced northward heat transport and extended sea-ice cover (Renssen et al., 2010; Roche et al., 2010; Thornalley et al., 2011; 2013). ~~For instance, several studies have found that the global ocean circulation is sensitive to freshwater fluxes generated from the melting ice sheets in terms of varying locations related to deep convection and flow rates (Renssen et al., 2010; Roche et al., 2010). Indeed, proxy-based evidence suggested that ice sheet melting in the early Holocene and the resulting freshening of the surface ocean slowed down the Atlantic Meridional Overturning Circulation (AMOC), leading to reduced northward heat transport, and then cold conditions and extended sea ice cover over mid and high latitudes (Thornalley et al., 2009; 2011; 2013). In addition, compared to ice-free surfaces, the surface albedo was much higher over the ice sheets, also resulting in relatively low temperature. Furthermore, the topography of ice sheets also can influence the climate through adjustment of the atmospheric circulation which can vary from region to region (Felzer et al., 1996; Justino & Peltier, 2005; Langen & Vinther, 2009). For instance, topography of ice sheets generated the glacial anticyclone that locally cooled the temperature (Felzer et al., 1996). In contrast, the topography effects of ice sheet caused a 2–3 °C warming over the North Atlantic under the Last Glacial Maximum (LGM) context (Pausata et al., 2011; Hofer et al., 2012). However~~Overall, the net effect of ice sheets on the early Holocene climate can be expected to have tempered the orbitally induced warming ~~caused a cooling in~~ at the mid and high latitudes~~ when all of these ice sheet related aspects – orography, extent and the meltwater – are taken into account~~. ~~For the early Holocene, although the ice sheets were substantially reduced in scale compared to the LGM, the net cooling effect of the ice sheets still can be seen, and they tempered the impact of the orbitally forced summer insolation maximum (Renssen et al., 2009). The regional differences caused by the impact of ice sheets relative to insolation were reflected by the clear regional variations in timing of the Holocene thermal maximum (HTM) among similar latitudes. For instance, Alaska had a much earlier HTM than eastern Canada (Kaufman et al., 2004). However, the main sources of uncertainty on early Holocene climate change are associated with the dynamics of ice sheets and the related freshwater release. For example, deglaciation reconstructions are primarily based on dating of geological features and correlating these geological datasets between regions (Dyke et al., 2003; Svendsen et al., 2004; Putkinen & Lunkka, 2008; Stokes et al., 2015). Recent studies based on cosmogenic exposure dating indicate slightly older ages of deglaciation in some regions than suggested by radiocarbon dating (Carlson et al., 2014; Clark in preparation), because a large uncertainty in bulk organic sample's ages and the possibility of old carbon contamination (Carlson et al., 2014; Stokes et al., 2015).~~ Important adjustments~~The changes in~~

~~ocean during the early Holocene impacted~~ in the carbon cycle occurred in the early Holocene, as evidenced by the rise in atmospheric CO_2 levels by 20–30 ppm that contributed to the warming (Schilt et al., 2010). ~~as the oceans are a huge natural carbon reservoir, and influenced the CO_2 concentration in the atmosphere through interactions (Sarnthein et al., 1988). During the early Holocene, the atmospheric CO_2 level increased by 20–30 ppm (Marchitto et al., 2007; Schilt et al., 2010), primarily because of the increasing wind-driven upwelling in the Southern Ocean, leading to an increasing ventilation of the deep ocean (Anderson et al., 2009). Important c~~Changes also happened in the biosphere during the early Holocene also~~ in the biosphere~~. ~~In particular, vegetation~~ Vegetation reconstructions ~~based on pollen and macrofossils~~ revealed a northward expansion of boreal forest in the circum-Arctic region after the retreat of the ice sheets (MacDonald et al., 2000; Bigelow et al., 2003; CAPE project 2001; Fang et al., 2013). This expansion of boreal ~~coniferous~~ forest into regions ~~which~~ that were not previously ~~not~~ vegetated or were covered by tundra caused a reduction of the surface albedo and induced a positive feedback to the warming trend (Claussen et al., 2001).

The impact of all these ~~external and internal~~ forcings on the Holocene climate ~~of the early Holocene~~ has been examined in ~~transient~~ modelling studies. The particular focus in these studies has been on the influence of the LIS and Greenland ice sheet (GIS) decay on the climate after 9 ka relative to other climate forcings (Renssen et al., 2009; Blaschek & Renssen, 2013). ~~In transient simulations performed with the ECBilt-CLIO-VECODE model,~~ Renssen et al. (2009) used transient simulations performed with the ECBilt-CLIO-VECODE model, and found that the Holocene climate was sensitive to ice sheet ~~configuration~~ and that the LIS cooling effects ~~of the LIS~~ delayed the ~~timing of the~~ Holocene Thermal Maximum (HTM) by up to thousands of years. Blaschek and Renssen (2013) applied a more recent version of the same model (renamed as LOVECLIM) and revealed that the GIS melting had an identifiable impact on the climate over the Nordic Sea ~~by weakening the AMOC and causing expansion of sea ice~~. However, these Holocene modelling studies only started at 9 ka, implying that the climate of the early Holocene between 11.5 and 9 ka ~~-~~ was~~has~~ not included in these studies~~yet been~~ ~~simulated~~. The most important challenges in simulating climate during this initial phase of the early Holocene are the inherent uncertainties in the ice-sheet forcings in terms of the ice sheet dynamics and the related meltwater release. Recent deglaciation studies based on cosmogenic exposure dating indicate slightly older ages of deglaciation in some regions than suggested by radiocarbon dating data (Carlson et al., 2014; Clark in preparation), primarily because of a large uncertainty in bulk organic sample ages and the possibility of old carbon contamination (Carlson et al., 2014; Stokes et al., 2015).~~For example, large discrepancies exist between different estimated timings of the final FIS decay (Lundqvist & Saarnisto, 1995; Dyke et al., 2003; Occhietti et al., 2011; Clark in preparation). Moreover~~Furthermore, the Younger Dryas stadial ended at 11.7

ka and may still have influenced the early Holocene climate due to the long response time of the deep ocean (Renssen et al., 2012). Therefore, the climate system's response to forcings before 9 ka ~~the climate system's response to forcings~~, especially to ice sheets, is poorly comprehended.

~~Here, w~~We have extended the study of Blaschek and Renssen (2013) back to 11.5 ka in the present study~~for~~ to explore~~ing~~ the early-Holocene climate response to these key forcings~~ in the northern extratropics~~. ~~We~~ By employing the same climate model of intermediate complexity LOVECLIM, ~~that includes dynamical components for the atmosphere, ocean, sea ice and vegetation. W~~we first analyzed the impact of forcings on the climate at 11.5 ka ~~in equilibrium experiments~~ and subsequently investigate the influence of two ice-sheet deglaciation scenarios in transient simulations. ~~By~~ The ~~comparing the~~comparison of these different simulations ~~we~~ enable us ~~try~~ to disentangle how the ~~dynamic~~ ice sheets influenced the early-Holocene climate~~ and the possible mechanisms~~. More specifically, we have addressed the following research questions: 1) What ~~are~~ were the ~~main~~ spatial patterns~~characteristics~~ of simulated temperature at the onset of the Holocene (11.5 ka)? 2) What ~~is~~ were the roles of forcings, especially ice sheet decay, in shaping these features~~characteristics and what are possible other mechanisms~~? 3) What was the spatiotemporal variability in ~~are~~ the simulated early Holocene temperature evolution~~overall features of the temperature evolution and the early Holocene warming in different regions~~?

2 Model and experimental design

2.1 The LOVECLIM model

We conducted our simulations with version 1.2 of the three-dimensional Earth system model of intermediate complexity LOVECLIM (Goosse et al., 2010), in which the components of the atmosphere, ocean ~~and~~ including sea ice, vegetation, ice sheets and carbon cycle are dynamically included. However, in our version, the components for ice sheets and the carbon cycle were not activated. ~~Accordingly~~Therefore, the ice sheet configuration was prescribed in our present study. The atmospheric component is the quasi-geostrophic model ECBilt ~~coupled to a land-surface model. It~~that consists of ~~3~~ three vertical layers and has T_{21} horizontal resolution (Opsteegh et al., 1998). CLIO is the ocean component which consists of a free-surface, primitive-equation oceanic general circulation model (GCM) coupled to a three-layer dynamic-thermodynamic sea-ice model (Fichefet & Maqueda, 1997). The ocean model includes 20 vertical levels and a 3°x3° latitude-longitude horizontal resolution (Goosse & Fichefet, 1999). These two core components were further coupled to the biosphere model VECODE, which simulates the dynamics of two main terrestrial plant functional types, trees and grasses, ~~as well as~~in addition to desert (Brovkin et al., 1997). More details on LOVECLIM can be found in Goosse et al. (2010).

The LOVECLIM model is a useful tool to explore the mechanisms behind climate change and it has made critical contributions to our understanding of ~~Holocene~~ the long-term climate change in the Holocene observed in proxy records (Renssen et al., 2005; 2006; 2010). For example, it has helped the investigation of the potential forcings behind the Younger Dyras (Renssen et al., 2002; Wiersma et al., 2006, Renssen et al., 2015), and the role of the decaying LIS and GIS melting in the temperature evolution over the last 9 ka (Renssen et al., 2009; Blaschek & Renssen, 2013).~~experiments with realistic freshwater perturbations for the 8.2 ka event reproduced a climate anomaly that compared favorably with proxy data both with respect to magnitude of the cooling and the duration of the events (Renssen et al., 2002; Wiersma et al., 2006). Transient experiments of the last 9 ka have revealed that the decaying LIS delayed the timing of HTM in terms of temperature evolution (Renssen et al., 2009) and that the climate was sensitive to GIS melting (Blaschek & Renssen, 2013) during the Holocene.~~ Moreover, ~~T~~the LOVECLIM model simulates a reasonable modern climate~~, as the simulation set up with present-day forcing is able to capture the main characteristics of the observed temperature distribution in the extratropics~~ (Goosse et al., 2010)~~, although the model seems to overestimate the temperature over the tropics and produces a weaker temperature gradient between the Eastern and Western Pacific Ocean than observed~~.~~ Moreover, the model~~ It also simulates a reasonably well-meridional overturning streamfunction and reproduces a large-scale structure of atmosphere circulation which agrees with observations ~~the data-based estimates~~ and with other models (Goosse et al., 2010).~~, even though the simulated sea ice extent is better in the Pacific than in the Atlantic. It also reproduces a large-scale structure of atmosphere circulation which is comparable with observations, except for a slightly weaker Aleutian low and a location shift of the Icelandic low (Goosse et al., 2010).~~ In addition, the model's sensitivity to freshwater perturbation is reasonable compared to that of other models (Roche et al., 2007), and it sensitivity to a doubling of atmospheric CO_2 concentration is 2 K, which is in the lower ~~range~~ end of estimation in of coupled general circulation models (GCMs) (Flato et al. 2013~~Martinez-Boti et al., 2015; Palaeosens Members 2015~~).

2.2 Prescribed forcings

We included the major climatic forcings in terms of greenhouse gas (GHG)~~ concentrations~~ in the atmosphere, astronomical parameters (orbital forcing or ORB) and decaying ice sheets. In all simulations, the solar constant, aerosol levels, the continental configuration and bathymetry were kept fixed at preindustrial values. ~~Considering the greenhouse gas (GHG) forcing, we~~We based the concentrations of CO_2, CH_4 and N_2O on ~~measurements in~~ ice cores measurements for GHG forcing

(Loulergue et al., 2008; Schilt et al., 2010). ~~From the onset of the Holocene, t~~The radiative GHG forcing anomaly (relative to 0 ka) in W m^{-2}, representing the overall GHG contribution, at first showed~~ first~~ a rapid rise with a peak of -0.3 W m^{-2} at 10 ka, which was followed by a slight decrease towards a minimum at 7 ka, and gradual increase towards 0 ka (Fig. 1). ~~For the orbital configuration (ORB), the values of the~~ The astronomical parameters (~~,~~ eccentricity, obliquity and longitude of perihelion~~, which determine the latitudinal and seasonal distribution of solar radiation at the top of atmosphere~~) determine the incoming solar radiation at the top of atmosphere, and were derived from Berger (1978). A~~s a~~n example of the ~~resulting~~ change in insolation is shown for~~,~~ the anomaly for June at 65° N(~~ is~~ plotted in Figure 1), which show~~sing~~ the gradual decrease over the course of the Holocene. At the beginning of the Holocene (11.5 ka), the orbitally-induced insolation anomaly in the ~~Northern Hemisphere (~~NH~~)~~ was positive in summer and negative in winter (Fig. ~~2~~SI1). ~~At the same time, the global annual-mean insolation stayed almost at the same level (not shown). Therefore, the obliquity is most likely the major contributing factor for the orbital forcing in this case.~~ Overall, this setup of GHG and ORB forcing is in line with the PMIP3 protocol (http://pmip3.lsce.lsce.ipsl.fr), except ~~for the~~that our simulation excluded the increase~~s~~ in GHG levels ~~in~~ during the industrial era~~, which were excluded~~ (Ruddiman, 2007).

~~For the ice sheet forcing, w~~We took three aspects into account concerning the ice sheet forcing,~~—~~ namely, their spatial extent, their thickness and their meltwater discharge. The reconstructions of ice-sheet spatial extent ~~and deglaciation~~ are ~~primarily~~ based on the dating of geological features~~, such as former end moraines and glaciated terrain,~~ and on the correlation of these geological datasets between different regions (Dyke et al., 2003; Svendsen et al., 2004; Putkinen & Lunkka, 2008). ~~According to the reconstructions, at 11.5 ka~~ T~~t~~he ice sheets at 11.5 ka covered most of Fennoscandia except for southern Scandinavia and eastern Finland (Svendsen et al., 2004; Putkinen & Lunkka, 2008; Clark in preparation). The LIS occupied most of the lowland area north of the Great Lakes region and filled the whole Hudson Strait (Licciardi et al., 1999; Dyke et al., 2003; Occhietti et al., 2011). The relative thickness of LIS was up to 2000 m, and for the FIS this was about 100 m~~According to~~ (Ganopolski et al. ~~(~~2010), which is comparable with the ICE-5G reconstruction (Peltier 2004). ~~the relative thickness of LIS was up to 2000 m, while for the FIS this was about 100 m.~~ Both the spatial extent of the ice sheet and ~~the~~ its ~~maximum~~ thickness were updated every 250 yrs in our transient experiments, and they decreased rapidly during the earliest Holocene, followed by a more gradual deglaciation rate from 8 ka onward (Fig. 2~~3~~a).

~~In our equilibrium experiments for 11.5 ka, w~~We applied the meltwater release for 1200 yrs in our equilibrium experiments for 11.5 ka by adding 0.11 Sv (1 Sverdrup is~~:~~ 10^6 m^3/s) of freshwater at the St. Lawrence River and 0.05 Sv at Hudson Strait and Hudson River, 0.055 Sv from FIS and 0.002

Sv from GIS (Licciardi et al., 1999; Jennings et al., 2015). ~~In our transient experiments that covered the last 11.5 ka, t~~The total freshwater volume added ~~in~~to the oceans in our transient experiments ~~due to ice sheet melting~~ was about 1.46x10^{16} m^3 in the first 4700 yrs (Fig. 2b), which roughly matches ~~with~~ the estimated ~~volume of~~ ice ~~-~~sheet ~~melted~~ melting volume during~~in~~ the early Holocene (Dyke et al., 2003; Ganopolski et al., 2010; Clark in preparation). The volume of meltwater is slightly lower than the volume of the estimated 60 m sea level rise that took place during the early Holocene (Fig. 2c) (Lambeck et al., 2014), ~~thus suggesting~~which suggests a coeval Antarctic melting contribution that is not considered here. Given the lack of a direct ~~climate~~ imprint left by meltwater on terrestrial records and hence the relatively large uncertainty ~~in freshwater forcing~~, we used two versions of the freshwater flux (Fig. 2~~3~~b) that represent two possible deglaciation scenarios of the GIS and FIS, named FWF-v1 and FWF-v2. The GIS FWF_v1 scenario is derived from the ICE_5G reconstruction, and FWF_v2 is based on the reconstruction of Vinther et al. (in 2009) that suggests a faster GIS thinning. The two FIS fwf scenarios are based on two estimations of the FIS melting, since the recent cosmogenic dating (FWF_v2) supports a faster melting (Clark in preparation) than previously thought (FWF_v1). ~~Compared to FWF-v1, the second version of freshwater flux included a larger GIS contribution in the earliest Holocene (before 9ka) in agreement with Vinther et al. (2009), and a more gradually decreasing melting rate of the FIS.~~ However, we kept the freshwater discharge from LIS ~~stayed~~ the same as in version-1, since the LIS deglaciation has been relatively well studied and we are more certain about its contribution.

2.3 Setup of experiments

We performed two types of experiments: equilibrium and transient simulations. Firstly, a series of equilibrium experiments with boundary conditions for 11.5 ka (Table 1) were designed, of which only two simulations are presented here: OG11.5 ~~with only ORB and GHG forcings,~~ and OGIS11.5. ~~with full forcing (including the ice sheets)~~ OGIS11.5 includes ice sheet forcing while no ice sheets are included in OG11.5 (Table 2). Each of these experiments was run for 1200 yrs, initiated from the model's default modern condition ~~to spin-up~~ and the last 200 yrs of data were used for the analysis.~~;~~ ~~as~~ Renssen et al. (2006) have demonstrated that ~~such~~ a 1200-year spin-up is sufficient to ~~produce a realistic climate~~reach a quasi-equilibrium in all components of the model.

The end of the 1200-yrs equilibrium runs was then taken to ~~obtain realistic~~ initialize ~~conditions for three~~the transient experiments that covered the last 11.5 ka. In the first transient simulation named ORBGHG, both GHG and ORB vary on an annual basis. In the second simulation OGIS_FWF-v1, the ice sheet topography (Fig. 2a) and FWF_v1 (Fig. 2b) were additionally included~~the ice sheet forcing in terms of the ice extent and elevation (Fig. 3a) was included in addition to GHG and ORB, and the version 1 of freshwater flux (Fig. 3b) was applied~~. ~~A comparison between ORBGHG and~~

~~OGIS_FWF-v1 allows us to explore the influence of ice sheets. In order t~~To further investigate the ~~sensitivity of~~ climate response to the relatively uncertain freshwater forcing ~~related to the melting of GIS and FIS~~, a third experiment (named OGIS_FWF-v2) was performed with the freshwater version-2 ~~freshwater~~ (Fig. ~~3c~~2c), while the ice sheet topography ~~of all ice sheets~~ was kept the same as in OGIS_FWF-v1. A pre-industrial experiment (PI) was run for 1200 yrs from the model's default ~~modern condition~~ with the boundary conditions in Table 1 and, similarly as for the other equilibriums, the results of the last 200 yrs were used as a reference. These simulations and their forcings are summarized in Table 2. All temperature values in this study are shown as deviations from ~~this reference~~PI. The temperatures presented here are simulated surface temperature values without the environmental lapse rate corrections to the sea level temperature, implying around 0.5°C cooler bias over ice sheet covered region when compared with site specific proxy records.

3 Results

~~In the first part of this section, our analysis and discussion of temperatures is based on equilibrium experiments, which are designed to study the response of the climate to the main forcings at 11.5 ka and to obtain the realistic 11.5 ka climate state. Then, in the second part, based on the analysis of the first part, we mainly focus on the transient simulations for tracing the temperature evolution during the last 11.5 ka.~~

3.1 Equilibrium experiments at the onset of the Holocene

3.1.1 Simulation with only ORB & GHG forcings at 11.5 ka (OG11.5)

In experiment OG11.5, summer temperatures ~~are~~ were 2–4°C higher over most of extratropical continents than in ~~our preindustrial reference run~~the simulation of PI, with the maximum ~~difference of~~deviation of 5°C in the central part of continents (Fig.4a). The warming over the oceans was a about 1.5°C , ~~is~~ and less conspicuous than that of continents~~with a 1.5 °C warmer climate, indicating lower sensitivity of oceans to the prescribed forcings than continents~~. ~~As all atmospheric greenhouse gas levels were lower at 11.5 ka than in preindustrial era (Fig. 1), t~~The warmer conditions ~~in OG11.5 are~~were caused by the orbitally-induced positive summer insolation anomaly, as all atmospheric greenhouse gas levels were lower at 11.5 ka than in preindustrial era (Fig. 1). The most obvious feature of the simulated winter temperature anomaly ~~is~~ was the marked contrast between high latitudes and areas more to the South (Fig. 3~~4~~b). For instance, the mid-latitudes ~~are~~ were 1.5–3°C cooler ~~than in the reference run PI~~ with the strongest cooling in the central ~~part of~~ continents, ~~while~~ whereas the high-latitude Arctic is clearly warmer with a maximum up to +3°C than in the PI. This latitudinal gradient can be seen in the annual mean temperature as well. Annual mean temperatures over the Arctic are about 1–4°C higher than in the PI with slightly stronger warm climate in winter than in summer, which indicate the Arctic Ocean damping effect on a seasonal signal due to a large heat capacity. The temperatures were roughly unchanged (mostly within 0.5°C, Fig. 3c) over the southern regions with a stronger seasonality (with warmer summer and cooler winter), which is consistent with the insolation change at 11.5 ka (Fig. 2). ~~With the exception of the Arctic, the OG11.5 results clearly reflect a stronger seasonality than present day with warmer summer and cooler winter, which is consistent with the insolation change at 11.5 ka (Fig. 2). Annual temperatures are about 1–4 °C higher at the high latitudes compared to the PI, whereas in temperate regions the temperatures are roughly unchanged (mostly within 0.5 °C, Fig. 4c).~~

3.1.2 Climate response to melting ice sheets at 11.5 ka (OGIS11.5)

~~As expected, o~~Our simulation OGIS11.5 (including the impact of 11.5 ka ice sheets) suggests a much cooler climate than ~~in the~~ that of in the OG11.5~~ ka experiment~~. Most notably, ice sheets induced ~~change the summer temperature pattern by inducing~~ a strong summer cooling over ice-covered areas, and reduced~~ing~~ temperatures by 5°C compared to ~~our reference run~~the PI, with ~~maximum~~ a strongest cooling at the center of the LIS~~ and FIS~~. Additionally, the SST ~~sea surface temperature is~~ was also more than 1.5°C lower over N Atlantic Ocean. In contrast,~~ summer~~ temperatures over the ice-free continents ~~are~~ were mostly above the preindustrial level~~ over the ice-free continents~~, but still lower than those found in the OG11.5, except for ~~NW Canada and~~ Alaska region.

~~Despite the impact of the ice sheets in~~ The simulation OGIS11.5 in winter~~,~~ indicated ~~the~~ warmer central Arctic ~~remains warmer in winter~~ than in the ~~preindustrial era~~PI~~, similar to the results of OG11.5. On the other hand~~, although the area with colder conditions clearly expands in OGIS11.5 ~~compared to~~than in the OG11.5, with anomalies ~~reaching well~~fell below -5°C. Alaska wa~~i~~s the only continental region where the winter temperatures ~~are above~~exceeded the preindustrial ~~mean~~ values by up to +3°C. ~~As expected, the maximum~~ The strongest cooling effect ~~is~~ was present in the regions covered by ice sheets, for instance more than 3°C cooler over the LIS.

~~In OGIS11.5, t~~The simulated ~~annual~~ mean temperature ~~anomalies~~ in OGIS11.5 clearly showed ~~that the~~an overall cooler climate ~~is cooler~~ than in the PI due to the ice sheet impact~~ of the ice sheets~~ (Fig. 4f). The Eurasian continent ~~is~~ was mostly 1.5–3°C cooler, and a maximum temperature reduction of more than 5°C ~~is~~ was simulated over the LIS~~ and FIS~~. Only two areas are still warmer: Alaska, including the adjacent sector of the Arctic Ocean, and the Nordic Seas. The most distinct feature~~ in OGIS11.5 is~~ was thus a thermally contrasting pattern over North America, with simulated temperatures being around 2~~-~~°C higher than those~~the preindustrial reference~~in the PI ~~in~~ for Alaska, ~~while~~ whereas ~~in~~ over most of Canada the temperatures are more than 3~~-~~°C lower.

3.2 Transient simulation for the Holocene

~~To further investigate the potential impact of ice sheets on the temperature trend we now analyze the transient simulations. In our analysis in section 3.1, I~~I~~i~~t ~~became~~is clear in our analysis of section 3.1 that the climate ~~shows~~ showed different responses in the following areas: the Arctic, NW Europe, N Canada, Alaska and Siberia (marked in Fig. S2~~1~~). Therefore, these areas are selected for special examination and the temperature evolutions of these regions will be shown. ~~Since o~~Our major focus ~~is~~ was on the millennial-scale temperature trends, therefore we applied a 500-yr running mean to our simulated time-series that~~,~~ effectively ~~filtering~~ filtered out high-frequency variability.

3.2.1 Temperature evolution in the Arctic

~~In the simulation ORBGHG,~~ T~~t~~he Arctic summer temperature in the ORBGHG~~in the Arctic~~ continuously decreases, which ~~resulting~~ resulted in a total cooling of 2~~-~~°C during the Holocene. The winter temperature ~~shows~~ showed an even stronger overall cooling, ~~that is even stronger, reaching~~that fell by about -3~~-~~°C~~, even though temperature slightly increases at the very beginning~~. Accordingly, ~~T~~the~~ simulated~~ annual mean temperature ~~displays~~ displayed a cooling that wa~~i~~s intermediate between that of the summer and winter seasons (Fig. ~~5~~4).

~~Compared to ORBGHG,~~ T~~t~~he simulation OGIS_FWF-v1 with full forcings reveals a more complicated climate evolution compared to that of the ORBGHG. ~~At the onset of Holocene,~~ T~~t~~he effect of ice sheets at the onset of Holocene caused~~s~~ the temperature in both summer and winter to be more than 2~~-~~°C lower than ~~in~~ those indicated by ORBGHG. It wa~~i~~s no surprise that the simulated effect of the ice sheets wa~~i~~s larger at the beginning of the Holocene than afterwards when the deglaciation ~~has~~ had progressed further. The final deglaciation of FIS happens at 10 ka and the corresponding deglaciation for LIS occurred at 6.8 ka. ~~(Fig.3a) and thus~~Therefore, their cooling effects no longer exist after 6.5 ka, and ~~therefore~~ all three runs showed similar temperatures after that time. As a consequence, the temperature evolution curve of OGIS_FWF-v1 first ~~shows~~ showed a warming, with the peak being reached at around 7 ka when the cooling effects of the ice sheets ~~are~~ had been counterbalanced by the insolation. ~~,~~ This was subsequently followed by a gradual cooling that is controlled by the orbital forcing. The temperature initially had ~~increases~~ increased ~~till~~ by ~~around~~ 6.5 ka at rate of about 0.26, 0.21 and 0.44~~0.35, 0.28 and 0.51~~°C ka^{-1} for summer, winter and annual temperature, respectively. The ~~simulation~~ OGIS_FWF-v1 simulation indicated~~s~~ that the summer climate in Arctic ~~experiences~~ experienced a slightly faster warming at the beginning, followed by a more gradual warming ~~till~~ toward the maximum anomaly of 1~~–~~°C warmer than

~~present day~~PI at about 7.5 ka (Fig. 4~~5~~a). The simulated winter temperature ~~stays~~ stayed at a lower level~~, being~~ that was 2 °C lower than that of ~~in~~ ORBGHG ~~till~~ before 7 ka, followed by a rapid increase of about 1.5 °C within 500 yrs, and then ~~reaching~~ reached a ~~warm~~ temperature ~~maximum~~ peak of about 1.5 °C warmer than ~~today~~in the PI. The simulated annual mean temperatures showed a relatively stable rise until~~l~~ 6.5 ka, which ~~reaching~~ reached a maximum of about 1.5 °C warmer than the ~~reference~~PI. The simulation OGIS_FWF-v2 ~~gives~~ gave ~~rather~~ similar results ~~in~~ forthe Arctic, but had~~s~~ an even cooler climate before 9 ka than in OGIS_FWF-v1 with the maximum cooling of up to 0.3 °C ~~in~~ for all seasons at 10.5 ka.

3.2.2 Temperature evolution in Northwestern Europe

~~In the domain of Northwestern Europe,~~ ORBGHG indicates smaller climate variability in NW Europe, ~~during all seasons~~ than in the Arctic. The temperature ~~declines~~ declined by around 1.5°C ~~over~~ through the entire period in summer, less than 0.5 °C ~~in~~ for annual mean and ~~rises~~ rose by 0.5 °C in winter (Fig.6) , which implied a stronger seasonality than in preindustrial period. This contrasts markedly with the clear cooling of climate in each season in the Arctic~~, and implies a stronger seasonality than in the preindustrial period~~.

The ~~simulation~~ OGIS_FWF-v1 simulation ~~shows~~ showed an overall cooler climate in NW Europe at the onset of Holocene~~ than at 0 ka~~, with the temperature anomalies of -1.5 °C in summer , -3 °C in winter and -2.8 °C in annual mean compared to ~~the pre-industrial era~~PI. ~~From that time on, t~~The temperatures increased in ~~the early Holocene~~this point toward 6 ka at an overall rate of ~~0.73, 0.51 and 0.55~~ 0.28, 0.48, 0.54°C ka^{-1} for summer, winter and annual mean, respectively. The most important feature in summer is a sharp rise of temperature from a negative anomaly (-1.5 °C) to a positive one (+1 °C) by 10 ka, when the~~a~~ first peak wa~~i~~s reached. Subsequently, a slight cooling is noted before~~till~~ 8 ka, followed by another temperature increase, which leads to a second warming peak at 7.4 ka. ~~In winter,~~ T~~t~~he climate in winter~~shows~~ showed a relatively stable warming ~~till~~ by 6.5 ka with no identifiable warm peak. The annual temperature ~~reflects~~ reflected the same phases of warming as in summer, one before 10 ka and another before 7.5 ka, but without a clear early temperature ~~maximum~~peak. ~~From around 7 ka, the~~ T~~t~~emperatures in all seasons from around 7 ka, followed the ORBGHG simulation. It is worth noticing that the ~~simulation~~ OGIS_FWF-v2 simulation produce~~d~~s a further cooling~~er climate~~ in summer between 11.5 and 9 ka ~~than~~ relative to the OGIS_FWF-v1, which ~~is~~ was also reflected in the annual mean. As a result, there wa~~i~~s only one clear thermal maximum in summer for NW Europe, which ~~peaking~~ peaked at about 7.4 ka.

3.2.3 Temperature evolution in Northern Canada

~~In ORBGHG,~~ S~~s~~imulated temperatures in ORBGHG for~~in~~ N Canada decrease by 2.2 °C in summer, 0.6 °C in winter and 1.1 °C in annual average during the Holocene (Fig.7). The stronger cooling in summer than in winter ~~reflects~~ reflected the strong early-Holocene seasonality, which decreases over the whole period.

The ~~simulation~~ OGIS_FWF-v1 simulation ~~produces~~ described a much cooler climate in N Canada during the early Holocene than that indicated by the ~~in~~ ORBGHG. ~~Compared to ORBGHG, t~~The cooler climate ~~is cooler~~was up to 5°C for all seasons at the onset of Holocene ~~by more than 5 °C in all seasons~~. ~~As expected, t~~The climate ~~in N Canada is~~ dramatically ~~warming~~ warmed up with an overall large rate of more than 1°C ka^{-1} in both ~~varying from 1.37 °C ka^{-1} in~~ winter and ~~to 1.88 °C ka^{-1} in~~ summer ~~in~~ during the early Holocene, which was due ~~owning~~ to the impact of ~~gradually~~ decaying LIS. The early Holocene warming wa~~i~~s however not linear~~, as~~ because an initial phase with more rapid warming ~~i~~was followed by a more gradual temperature increase. In summer, ~~the~~ this warming ~~results~~ resulted in a thermal ~~maximum~~ peak at around 7.4 ka, which ~~that~~ wa~~i~~s about 1.5°C warmer than ~~at~~ in PI~~preindustrial period~~. From ~~that time on~~7.4ka onwards, the climate ~~experiences~~ experienced a gradual cooling that is very similar to that of the ORBGHG. ~~Compared to summer, t~~The simulated temperatures in winter and annual mean do not show such a clear ~~thermal maximum~~warm peak in comparison to summer. The results of OGIS_FWF-v2 only indicate marginal differences relative to OGIS_FWF-v1 ~~in~~ for all seasons. Overall, the most significant feature ~~in~~ of the simulated temperature ~~evolution~~ in N Canada is the strong~~impressive~~ warming that took place in the early Holocene.

3.2.4 Temperature evolution in Alaska

~~In Alaska,~~ T~~t~~he ORBGHG simulation ~~represents~~ showed an overall cooling trend in Alaska for all seasons. The simulated summer and annual mean temperatures experienced a decrease ~~by~~ of more than 2 °C ~~over~~ throughout the whole period. The winter temperature had slightly ~~increases~~ increased ~~till~~ by ~~about~~ 10 ka, and then ~~stays~~ stayed about 2 °C higher ~~than in the PI~~ for ~~about~~ period of 800 yrs, which was followed by a constant decrease toward the preindustrial era~~reference~~.

In contrast to other areas, both summer and winter temperatures in OGIS_FWF-v1 showed an overall cooling trend in Alaska during the entire Holocene (Fig. 7~~8~~), which was slightly warmer than in our ORBGHG~~which is rather similar to our ORBGHG simulation, although the early Holocene is even slightly warmer in OGIS_FWF-v1~~. ~~As in ORBGHG, t~~The simulation OGIS_FWF-v1 indicates a 2 °C decline in summer temperature over the whole period, ~~although~~ and a slightly faster rate ~~than in ORBGHG can be~~occurred ~~seen~~ between 7 ka and 6.5 ka. The simulated winter temperature ~~is clearly higher than in ORBGHG at 11.5 ka, and~~ decrease~~s~~d by 3.5 °C ~~over~~ during the early Holocene, with two small ~~drops~~ declines at 9.5 ka and 6.7 ka. The annual temperature in the OGIS_FWF-v1 ~~reflects~~ reflected a 2.3 °C cooling during the Holocene. The OGIS_FWF-v2 simulation produced a rather similar Alaska temperature trend to that of the

OGIS_FWF-v1.~~The OGIS_FWF-v2 shows slightly cooler climate before 9 ka than OGIS_FWF-v1, especially in winter.~~

3.2.5 Temperature evolution in Siberia

~~In Siberia, summer temperature in~~ TheORBGHG ~~declines~~ described an~~by~~ almost 2~~-~~°C declines os summer temperature over Siberia during the last 11.5 ka (Fig. 8~~9~~). Simulation ~~W~~winter temperature showd~~s~~ a smaller variability, as it ~~decreasing~~ decreased by less than 1~~-~~°C~~ over the whole period~~, and~~while~~ the~~ simulated~~ annual mean temperature decreased~~s~~ by around 1~~-~~°C over the course of the Holocene. ~~Overall, in ORBGHG t~~The simulated temperatures evolution in ORBGHG over ~~in~~ Siberia wa~~i~~s ~~of~~ ona similar scale to that of NW Europe.

The difference ~~in~~ of simulated Siberian temperatures between ORBGHG and OGIS_FWF-v1 ~~varies~~ varied in summer and winter. On the one hand, the simulated summer temperature in OGIS_FWF-v1 ~~is~~ was generally similar to that in ORBGHG with the exception of a small warming of 0.7~~-~~°C before 10 ka~~, leading to a weak warm maximum~~. On the other hand, simulated winter temperature in OGIS_FWF-v1 ~~is~~ was around 2~~-~~°C lower than in ORBGHG before 7 ka~~. In OGIS_FWF-v1, winter temperature over Siberia stays lower and relatively stable level until 7 ka~~, followed by a rapid increase over the next 500 yrs after which it ~~follows~~ followed the ORBGHG simulation. Consequently, the simulated early Holocene ~~linear~~ warming lasted much longer ~~rate is much more prominent~~ in winter ~~(0.68 °C ka^{-1})~~ than in summer~~ (0.42 °C ka^{-1})~~. ~~The evolution of the annual mean temperature is intermediate between these two seasons. It is clear that the seasonality in Siberia also decreases from the early Holocene onwards.~~ The simulated Siberian temperatures evolution in OGIS_FWF-v2 generally ~~follows~~ followed that of the OGIS_FWF-v1.

4 Discussion

~~In order to~~We will evaluate our results~~, we~~by briefly compare the simulations with proxy-based reconstructions, which will be followed by an analysis of the mechanism behind the noted temperature patterns. ~~After that, t~~The impact of freshwater forcing will be discussed ~~in more detail~~ based on ~~our transient experiments~~the two fwf scenarios.

4.1 Comparison of simulations with proxy records

~~In Europe, climate reconstructions based biological proxies, including pollen and chironomids, consistently show that early Holocene's summer and winter climates were 0.5–2 °C and 1–3 °C cooler than at present (Mauri et al., 2015). Even though according to reconstructions of Mauri et al. (2015), the climate at 11 ka was warmer than the present in northernmost Scandinavia, the Alps and the Anatolian plateau mountain, this warmer climate is not consistent with the chironomid-based~~

~~reconstructions for Scandinavia and the Alps (Heiri et al., 2104). Additional geochemical evidence from lake sediments and speleothems, for example in Northern Norway also reflect cooler climate in the early Holocene than in the pre-industrial era (Lauritzen & Lundberg, 1999; Balascio & Bradley, 2012). This overall cool climate in reconstructions generally matches with our simulation OGIS11.5 that shows a lower annual temperature at 11.5 ka than the pre-industrial run.~~

~~In Siberia, proxies from lake sediments suggest different patterns from the east to the west. Geochemical proxies together with diatom and pollen data indicate lower temperatures in the early Holocene over eastern Siberia. For example, diatom and pollen assemblages and geochemical measurements (e.g. total organic carbon and concentration of pyrite) in lake sediments near the Lena River (Laing et al., 1999; Muller et al., 2009; Biskaborn et al., 2012; Klemm et al., 2013; Tarasov et al., 2013) consistently reflect a cooler climate than present day (Biskaborn et al., 2012). In western Siberia, reconstructions extending back to the early Holocene are relatively sparse. The available pollen-based reconstructions from Kharinei Lake and Lake Tumbulovaty, on the western side of the Ural Mountains, suggest similar summer temperatures in the early Holocene (within 1 °C deviations) as today (Salonen et al., 2011). By contrast, our simulation OGIS11.5 indicates that the annual mean temperature was about 1.5 °C lower at 11.5 ka than the pre-industrial era over the whole region, and is thus in better agreement with reconstructions in the eastern than in the western within Siberia.~~

~~In the Arctic, we compare our result with the sea ice cover reconstructions due to the scarcity of temperature reconstructions extending back to the early Holocene. Dinocyst-based reconstructions reveal diverse patterns of sea ice during the early Holocene among different parts of the Arctic: over the Barents Sea, a higher sea-ice concentration in the early Holocene than the recent period implies a cooler early Holocene (de Vernal et al., 2013), while only a minor sea ice change is found in the Canadian Arctic where the sea ice concentration is high throughout the whole Holocene. In addition, pollen-based temperature reconstructions from Melville Island (NW Canadian Arctic) show a 0.3 °C lower July temperature (Peros et al., 2010), and~~ ~~$\delta^{18}O$~~ ~~together with direct borehole temperature measurements from Greenland ice cores indicate about 3 °C cooler climate than the present (Dahl-Jensen et al., 1998; Vinther et al., 2008). Overall, these proxies suggest cooler conditions in the Barents Sea (eastern Arctic) and Greenland (Peros et al., 2010; de Vernal et al., 2013; Dahl-Jensen et al., 1998; Vinther et al., 2008), agreeing roughly with the simulated lower temperatures in our OGIS11.5 simulation than in PI. However, the reconstructed temperature signals from the Canadian Arctic are inconclusive (de Vernal et al., 2013), while our OGIS11.5 simulation reflects an overall warmer climate in the west and cooler in the east.~~

~~In addition, diatom assemblages, planktonic foraminiferal $\delta^{18}O$ and Mg/Ca data from the N Atlantic Ocean also indicate a slightly lower sea surface temperature (Came et al., 2007; Berner et al., 2008) in the earliest Holocene than at the present, which is in line with the simulated negative temperature anomalies in OGIS11.5. The estimated sea-ice coverage based on dinocyst assemblages from the Greenland Sea (MSM 712 core) suggests a minor negative sea ice concentration anomaly during 9-6 ka relative to the most recent 3 ka (de Vernal et al., 2013). This would support our simulated warmer conditions over the Greenland Sea if we assume that this negative sea ice concentration anomaly could extend back to 11.5 ka.~~

~~In North America, the proxies indicate significantly different patterns in the east and the west. In Central Beringia, the warmer summer during early Holocene is reflected by the peat accumulation and appearance of *Pinus pumila* in pollen assemblages (Anderson et al., 1988; Lozhkin et al., 2001; Jones & Yu, 2010). In Alaska, the higher-than-present temperature between 11.5 ka and 9 ka is reflected by northward expansion of animal and plant taxa (Kaufman et al., 2004). This warmer early Holocene in Alaska is also indicated by the earlier initiation of HTM (from 11 to 10 ka) represented by the compiled multi-proxy reconstructions (Kaufman et al., 2004). By contrast, in Eastern Canada the later initiation and termination of HTM (6 ka and 3ka, respectively, or even later in some areas) imply lower temperatures during the early Holocene (Kaufman et al., 2004), even though the temperature reconstructions in this region are limited by the fact that the region was covered by the LIS in the early Holocene. This thermal contrast within the same continent agrees well with our simulation OGIS11.5 in which warmer temperatures are simulated in Alaska, while a much cooler climate is found over Canada. Therefore, our simulation with full forcings (OGIS11.5) is able to capture the main features in temperatures that are commonly recorded by the proxies, and has better agreement with proxies in places where the density of reconstructions is relatively high (e.g in Europe) than in places where reconstructions are sparse (e.g western Siberia).~~

At the onset of Holocene, the overall cool climate indicated by reconstructions generally matches our OGIS11.5 simulation, which showed a lower annual temperature at 11.5 ka than in the PI. Climate reconstructions based on proxy data generally show a cooler early Holocene in N Europe than at the present both in summer and winter (Heiri et al., 2104; Mauri et al., 2015). Terrestrial and ocean sediment data also suggest a cooler early Holocene climate over eastern Siberia (Klemm et al., 2013; Tarasov et al., 2013) and a slightly lower SST over the N Atlantic Ocean (Came et al., 2007; Berner et al., 2008). Cooler conditions over the Barents Sea and Greenland also are indicated by multiple proxies (Peros et al., 2010; de Vernal et al., 2013; Vinther et al., 2008). Therefore, this proxy data agree with the simulated lower temperatures over these areas.

However, there is less agreement with proxies in places where the reconstructions are sparse. Only available pollen-based reconstructions from the western side of the Ural Mountains suggest a similar early Holocene summer (within 1°C anomaly) to that of as the present (Salonen et al., 2011), whereas OGIS11.5 indicates that the summer temperature was slightly higher at 11.5 ka over most areas. At the high latitudes, the sea-ice cover reconstructions serves as an indirect palaeoclimate proxy due to the scarcity of temperature records, and reveals an inconclusive temperature signals over the Canadian Arctic (de Vernal et al., 2013), whereas our simulation reflected an overall warmer climate in the west and cooler conditions in the east.

Proxies indicate significantly different climate patterns over the east and the west of N America. The later initiation and termination of HTM over N Canada imply lower temperatures during the early Holocene in the east (Kaufman et al., 2004). Whereas, the higher-than-present early Holocene temperatures over Central Beringia and Alaska are reflected by peat accumulation and by northward expansion of animal species (Kaufman et al., 2004; Jones & Yu, 2010). This thermal contrast agrees with those simulated patterns in the OGIS11.5, which indicate a warmer temperature for Alaska and a much cooler climate over Canada. However, this interpretation of high temperature was recently changed by Kaufman et al. (2016), who argued that the highest summer temperature in Alaska occurred as late as 8-6 ka. Hence our simulation agrees better with the interpretation of Kaufman et al. (2004). In general, our simulation with full forcings was able to capture the main temperature features that are also indicated in proxy-based reconstructions.

~~As for the temperatures evolution~~ Both stacked reconstructions (Shakun et al., 2012; Marcott et al., 2013) and our simulation OGIS_FWF-v2 show that the Holocene was generally characterized by an initial warming and subsequent Holocene warm period over the NH extratropics, which indicate the broad consistency between simulation and proxy data. However, there are some disagreements related to seasonality (Fig. 9). Marcott et al. (2013) interpreted the stacked temperature reconstruction representative of the annual mean climate, whereas it shows a better agreement with our simulated summer temperature than with annual mean value (Fig. 9). One potential explanation is that the proxy records have seasonal bias toward summer conditions, as has been suggested recently for many marine-based SST reconstructions (Lohmann et al. 2013). ~~, the multi-proxy reconstructions show that the Holocene was generally characterized by an initial warming and subsequent Holocene warm period over most of regions (Kaufman et al., 2004; Vinther et al., 2008; Brooks et al., 2012; Shakun et al., 2012). These features match with our simulation in which the temperatures rise during the early Holocene, reach a warm period and then gradually decrease to the present, with the exception of Alaska. Concerning the rate of warming in the early Holocene, $\delta^{18}O$ data and borehole temperature measurements from Greenland suggest a large overall warming rate~~

~~(0.8–1.9 °C ka^{-1}), while in Siberia and Norway, most reconstructions indicate that this rate is less than 1 °C ka^{-1} (Dahl-Jensen et al., 1998; Lauritzen & Lundberg, 1999; Johnsen et al., 2001; Vinther et al., 2009; Klemm et al., 2013; Tarasov et al., 2013). These proxy-indicated warming rates are similar to the rates suggested by our simulation. However, f~~Further region-by-region comparisons of these warming rates ~~(region by region)~~ with proxy records is hindered~~ by the scarcity of proxy data in some areas (e.g the Arctic) and the large variation between proxy reconstructions~~ limited space.

4.2 Mechanism of climate response to forcings

From our results, it is clear ~~It is obvious~~ that the spatial patterns of climate response at the onset of the Holocene can be attributed to the variation~~ous~~ in the dominant forcings prevailing in the different areas. Orbital scale insolation variation~~Orbitally induced insolation~~ is one of important driving factors for the early Holocene ~~temperatures~~climate. For instance, ~~in Alaska~~, the higher temperatures in Alaska ~~is~~ could be attributed to ~~primarily determined by~~ the orbitally induced positive insolation anomaly in combination with~~, which is also reflected by a relatively small variation between the simulations OG11.5 and OGIS11.5. Apart from the insolation, the~~ an anomalous atmospheric circulation caused by the remnant LIS~~, which is indicated by the 800 hPa Geopotential height (Fig.11), also played an important role (e.g. caused the slightly warmer climate) in Alaska~~. The air descends o~~O~~ver the cold LIS surface~~, the air descends~~, which ~~creating~~ created a high surface pressure anomaly that produces a clockwise flow anomaly at the surface, indicated by the 800 hPa Geopotential height (Fig.11). This would induce~~s~~ stronger southerly winds over Alaska ~~in OGIS11.5 than in OG11.5~~, which ~~that~~ advected relatively warm air from the South. A potential different early Holocene atmospheric circulation near the N Atlantic has also been reported by Steffensen et al. (2008) who found an abrupt transition of deuterium excess and a considerable reduction in dust concentration from the GRIP core data.

The strong influence of ice sheets on early Holocene temperatures has been found in previous ~~modelling~~ studies ~~which revealed the cooling impact of the LIS and thus delaying the HTM~~ (Renssen et al., 2009; 2012). The simulated lower summer temperatures over ~~the eastern part of~~ N ~~America~~ Canada and NW Europe in our simulation OGIS11.5 ~~compared to the preindustrial run~~PI is the result of such ice sheet-induced cooling~~ effect induced by ice sheets~~, which would fully overwhelm~~s~~ the warming effect of the positive summer insolation anomaly. The ice sheets~~s'~~ cooling effect~~, on a local scale,~~ can be partly explained on a local scale by the enhanced albedo over the ice sheets and by the climate's high sensitivity to ~~land~~ albedo change (Romanova et al., 2006). Indeed, the summer surface albedo over the ice sheets is much higher ~~exceeds (up to~~ 0.8~~), and is thus much higher~~ than ~~the albedo of~~ over ice-free surfaces where the values vary~~ing~~ from 0.1 ~~in mid-latitudes~~

to 0.5~~ in high latitudes~~, depending on the vegetation type and the fractional snow cover (Fig. 10). The temperatures can be further reduced by the ice-sheet orography impact. The elevation of ice sheets introduced descending air over ice-sheet surface, which caused the cooler condition on the local scale. There is also an approximate 0.5 cooling bias induced by the lapse rate effect compared with the site-based records. ~~Apart from the enhanced surface albedo, the orographic effect of the ice sheets can influence the climate as well, as the elevation is raised by several hundred metres with a maximum of up to 2000 m in the center of LIS. Actually, the previous studies have reported that the ice-sheet related elevation change has a notable effect on the atmosphere during the LGM, as it sets many features of surface pressure field, including the location of the subtropical highs and subpolar lows (Felzer et al., 1996; Justino & Peltier, 2005; Langen & Vinther, 2009). On the local scale, the glacial anticyclones over the ice sheets resulted from the descent of cool air from the high atmosphere cause the cooling of surface temperature (Felzer et al., 1996). At the onset of the Holocene, although the ice sheets were much smaller than during the LGM, they still had an identifiable impact in atmosphere. For instance, the descending air over the LIS created the anomalously high surface pressure and thus the changes in wind directions that influence the surrounding areas (Fig. 11), as already noted above. From the record side, the abrupt transitions of deuterium excess and the considerable reduction in dust concentration in the NGRIP ice core at the very beginning of Holocene also indicate a change in atmospheric circulation near the N Atlantic (Steffensen et al., 2008). The enhanced elevation over ice sheets also has a few degree cooling effect on temperature on a local scale if we take the environmental lapse rate into account.~~

~~The corresponding changes~~ Changes in vegetation and land cover ~~in~~ during the early Holocene contribute to climate change as well, especially over ecotonal regions. Modelling studies suggest that deforestation in boreal regions decrease the regional temperature by almost up to 1 °C due to an increase in surface albedo and related positive feedbacks ~~(biogeophysical effects)~~ (Levis et al., 1999; Claussen et al., 2001; Liu et al., 2006). ~~If we take~~Taking Siberia as an example, the insolation-induced warming was partially offset by the overall higher summer albedo (Fig 10) induced by the southward expansion of the tundra or/and bare ground and related feedbacks at 11.5 ka, which led to a minor warmer summer climate than PI. The albedo-related feedbacks and the smaller insolation anomalies annually counterbalanced each other at 11.5 ka, and resulted in a 0.5–2°C cooler climate. We are aware of the potential role of permafrost at high latitudes, however, the discussion of the impact of permafrost thaw is hindered by the fact that our model version did not include a dynamic permafrost module. A version of LOVECLIM that is coupled to a permafrost module (VAMPERS) is currently in development (Kitover et al. 2015), and should enable us to quantify the role of permafrost in a future study. ~~the summer climate is cooler in OGIS11.5 than the preindustrial over Siberia, which can be associated with the overall higher summer albedo in~~

~~simulation OGIS11.5 (some areas are up to 0.28) than in the PI (lower than 0.22). This is a consequence of the more southward extended tundra or/and bare ground which has a higher albedo than boreal forest at 11.5 ka compared with 0 ka. Apart from albedo-related feedbacks between boreal forest and tundra, the relatively small insolation deviation from the present over central Siberia also contributes to lower annual (0.5–1.5 °C) and winter (0.5–2 °C) temperatures at that time.~~

~~At the same time, m~~ Meltwater release and sea-ice related changes in the high-latitude oceans also ~~have~~ had a footprint in the early Holocene climate. The ~~simulation with full forcings~~OGIS11.5 simulation produced a ~~clear slowdown of the~~sluggish AMOC in the N Atlantic with the largest decrease being ~~maximum value decreasing by~~ more than 3 Sv. It was also reflected in a shallower overturning circulation at 11.5 ka compared to the PI period~~the preindustrial era~~ as a response to meltwater ~~generated from the deglaciation of ice sheets~~release (Fig. 12). This slowdown ~~in ocean circulation is consistent~~ also coincides with the ~~planktonic~~ foraminifera ~~records~~ data from the Arctic Ocean and Fram Strait ~~which~~ that suggest a reduced northward oceanic heat transport ~~through ocean circulation~~ (Thornalley et al., 2009). This slowdown and reduced heat transport led to a slightly lower temperature at~~in~~ high latitudes (western ~~part of~~ Arctic Ocean) at 11.5 ka than ~~in~~ that found in the ~~preindustrial period~~PI. Likewise, after the meltwater fluxes of the LIS diminished around 7 ka strong intensification of the AMOC followed. This sudden intensification of AMOC would explain the rapid Arctic temperature increase that occurred at this time (Fig. 4). However, it is worth noticing that the temperature decrease is not simply inversely linear with the amount of northward transport of heat since the sea-ice feedbacks further reinforce this change (Roche et al., 2007). Actually, sea ice coverage in OGIS11.5 was~~i~~s much more extensive over Davis Strait (N Labrador Sea) than the corresponding value in the OG11.5 (Fig. 13). This extended sea-ice cover in this region was stronger than the direct cooling effect of the reduced oceanic heat transport. Such an anomaly might be explained by ~~implying that~~ positive feedbacks involving sea ice were active (Renssen et al., 2005). ~~As for t~~The Greenland Sea warming~~, it~~ can be attributed to enhanced convective activity~~ here associated with the deep water formation,~~ that releases~~ing~~ more oceanic heat to the atmosphere. This enhanced convective activity ~~i~~was caused by the shift of deep water formation from the eastern Greenland Sea to the west, which wa~~i~~s initially induced by the freshwater discharge from ice-sheet melting~~ice sheets melting~~. ~~Overall, t~~The net overall response of climate ~~represents~~ reflects the impact of a combination of ~~ed~~ forcings and feedbacks, which showed a high temporal-spatial variability.~~significantly depending on the specific parameter's configuration which changes from region to region and from period to period.~~

4.3 Early Holocene warming and climate-ocean system response ~~of climate-ocean~~

~~system~~ to freshwater

~~Comparison of the full forcing simulations (OGIS_FWF-v1/2) with the control run (ORBGHG) reveals that the most important feature of the temperature evolution is the early Holocene warming that is present in most areas with varying magnitudes, with the exception of Alaska. This warming demonstrates the climate change from a cooler state, which was strongly influenced by the ice sheet cooling effects and related mechanisms, to an insolation-dominated warmer state.~~

The simulation of OGIS_FWF-v2 produced a stronger cooling in the Arctic and NW Europe than those found in the OGIS_FWF-v1 ~~from 11 to~~before 9 ka with a ~~maximum~~ stronger temperature reduction ~~before~~ around 10 ka. The enhanced freshwater influx from the GIS and redistributed meltwater from the FIS caused an alteration~~different~~ in the surface ocean freshening in the Nordic Seas, which ~~leading to~~ reduced convective activity (Renssen et al., 2010; Blaschek & Renssen, 2013). Indeed, this leads to a ~~slightly~~ further slight reduction of~~in~~ the northward heat transport by the Atlantic Ocean, which wa~~i~~s associated with a weakened AMOC ~~strength~~ (by 1-2 Sv):~~,~~ this in turn ~~producing~~ produced a slightly stronger cooling at 10 ka (Fig. S3~~14~~) and sea-ice ~~expansion of sea ice (Fig. 15), which is accompanied by slightly enhanced winter surface albedo in~~ over the Denmark Strait ~~in OGIS_FWF-v2 compared to OGIS_FWF-v1~~ (Fig. 14 & ~~16~~SI4).

The ~~applied~~ meltwater flux freshens the surface ocean in the deep-water formation area, ~~leading~~ which led to a slow~~ing~~ down ~~of~~ in the ocean circulation. However, the efficiency of this effect is determined by multiple aspects. The most important factor is the maximum flux of meltwater that was added to the ocean, while the total freshwater amount has only a second-order effect (Roche et al., 2007). ~~The n~~Numerous investigations on the behavior of the coupled atmosphere–ocean system suggest~~ed~~ that applying a certain amount of freshwater ~~in quasi-equilibrium~~ will not lead to a disruption of the North Atlantic Deep Water ~~(NADW)~~ production (NADW) as long as a threshold is not crossed (Ganopolski et al., 1998; Rahmstorf et al., 2005). Apart from the intensity and duration, the ocean circulation response ~~of ocean circulation~~ to freshwater also depends on the location where this freshwater is released. For instance, it is more sensitive to the release of freshwater ~~at~~ in the eastern Norwegian Sea than at the St. Lawrence River outlet since the former is closer to the main site with NADW formation (Roche et al., 2010). This is consistent with the previous study of Blaschek & Renssen (2103), ~~in which they~~who found that freshwater from the GIS did have a ~~non-ignorable~~ tangible impact on Nordic seas ~~and its circulation~~, even though the total amount wa~~i~~s minor. This location-depended sensitivity could also partially explain why the AMOC is weaker in OGIS_FWF_v2 than in OGIS_FWF-v1.

~~In NW Europe,~~ T~~t~~he OGIS_FWF-v1 produced two peaks of in the temperature over NW Europe,, at around 10 and 7 ka. High temperatures at 7 ka are ~~also~~ recorded in proxy-based reconstructions as well. However, no warm peak at 10 ka ~~can be~~was observed in pollen-based reconstructions, which suggests a cooler climate at 10 ka than present in Europe (Mauri et al., 2015). In contrast to OGIS_FWF-v1, the simulation with updated freshwater (OGIS_FWF-v2) produced a warming trend~~, which~~ that is consistent with a highest temperature around 7 ka. Moreover, the OGIS_FWF-v1 produced a temperature decrease between two peaks while the proxies suggest rapid temperature increase at the beginning followed by ~~the~~ a more gradual warming (Brooks et al., 2012). ~~Meanwhile, given the albedo's influences on temperature (Romanova et al., 2006), the albedo in the model has been checked and it turns out that the albedo value in the model is consistent with the vegetation of dwarf shrub and herb over Scandinavia at that time (Allen et al., 2010).~~ Therefore, from the viewpoint of the temperature evolutions in NW Europe, the OGIS_FWF-v2 represented a ~~is~~ more realistic climate than OGIS_FWF-v1 did, which implied that the existing uncertainties in the reconstructions of ice-sheet dynamics can be evaluated by applying different freshwater scenarios.~~implying a faster thinning of GIS as suggested by Vinther et al., (2009) and, correspondingly, larger meltwater release in early period would be more realistic.~~

5 Conclusions

We performed both equilibrium and transient simulations by employing the LOVECLIM climate model ~~in order~~ to explore the spatial patterns of the climate response to forcing at the onset of Holocene and the temperature~~s~~ evolution over the last 11.5 ka. ~~In our analysis, we~~ We focus on three research questions in our analysis, which are outlined below with main finding:~~.~~

1) What ~~are~~ were the ~~main~~ spatial ~~characteristics~~ patterns of simulated temperature at the onset of the Holocene?

The temperatures at 11.5 ka ~~are~~ were regionally heterogeneous~~,~~ compared with those of PI, which are shown as~~is represented by,~~ ~~-~~a range of annually negative anomalies over many areas ~~and~~ but which were ~~highlighted by~~ higher ~~value~~ in Alaska~~, compared with the preindustrial era~~. The climate ~~I~~in eastern N ~~America~~ Canada and NW Europe~~, the climate~~ was much cooler than those in other regions ~~reached the maximum cooling~~ with temperature anomalies of -2 to -5 °C relative to 0 ka throughout the year. The climate over the N Labrador Sea and the N Atlantic was also 0.5–3°C cooler. ~~For Siberia, t~~The temperatures in Siberia were 0.5–3 °C and 1.5–3 °C lower in winter and annual average, and summer temperature showed only a small deviation (between +0.5 to -1.5 °C) compared to ~~the preindustrial period~~0 ka. The summer temperature anomaly i~~I~~n the eastern ~~part of~~ Arctic Ocean ~~(over Barents Sea, Kara Sea and Laptev Sea)~~, ~~the summer temperature anomaly (between -0.5 and +0.5 °C)~~ was also small (between ±-0.5°C), and annual temperatures were 0.5–2 °C lower ~~than at 0 ka. In addition, the climate over the N Labrador Sea and the N Atlantic Ocean~~

~~were 0.5–3 °C cooler than the preindustrial during the whole year~~. In contrast to cooler condition in other areas, the temperatures in Alaska ~~in all seasons in Alaska~~ were 1.5–3 °C higher than pre-industrial period for all seasons.

2) What ~~is~~ were the roles of the forcings, especially ice sheet decay, in shaping these ~~characteristics~~features ~~and what are possible other mechanisms~~?

The ice-sheet cooling effect ~~The relatively cold climate at 11.5 ka~~ in ~~eastern~~ N ~~America~~ Canada and NW Europe ~~is a consequence of the ice sheets' cooling effects that~~ overwhelmed the warming impact of the positive insolation anomaly~~.~~, which caused the relatively cold climate at 11.5 ka. In particular, the enhanced surface albedo ~~of~~ over the ice sheets and the orographic effects were important for the cold conditions. The cooler climate over the N Labrador Sea and the N Atlantic was related to both reduced northward heat transport and activated sea-ice feedbacks which were initiated by weakened ocean circulation.~~For~~ A small summer temperature anomaly is found in Siberia, where ~~a small summer temperature anomaly~~ ~~in response to~~ the positive insolation anomaly was partially offset ~~surpassed~~ by the cooling effect of the higher albedo associated with the relatively extensive tundra cover~~which was more extensive~~ in the early Holocene ~~than at the present~~. The overall lower winter and annual temperatures can be attributed to both vegetation-related albedo feedbacks and to the relatively small negative insolation deviation ~~from~~ compared to the preindustrial ~~period~~ level over central Siberia.

The dominant factors for ~~In the~~ eastern ~~part of the~~ Arctic Ocean climate ~~(over Barents Sea, Kara Sea and Laptev Sea), the dominant factors for temperature~~ were the amount of northward heat transport associated with the strength of ocean circulation and the orbitally forced insolation ~~radiation anomaly~~ variation~~induced by orbital parameters~~. The annual mean temperature was lower than at ~~preindustrial era~~0ka because the cooling effect of a reduced northward oceanic heat transport (~~due to~~induced by weakened ocean circulation) was larger than the insolation-induced warming. ~~The~~ During summer, these two factors were of similar magnitude and temperatures ~~was~~ were similar to the preindustrial era ~~when these two factors were in similar magnitude~~. ~~The cooler climate over the N Labrador Sea and the N Atlantic Ocean was related to both reduced northward heat transport and to the sea-ice feedbacks initiated by weakened ocean circulation. In Alaska, the~~ T~~t~~emperatures in Alaska were higher ~~in~~ for all seasons in response to the dominant positive insolation anomaly and the enhanced southerly winds induced by the LIS, which advected relatively warm air from the South. Therefore, this regional heterogeneity is the result of the climate response to a range of dominant forcings and feedbacks~~through various mechanisms~~.

3) What was the spatiotemporal variability in the simulated~~are the overall features of the temperature evolution and the~~ early Holocene evolution~~warming in different regions~~?

The Holocene temperature evolution and early Holocene warming trend ~~are~~ were also geographically variable. In Alaska, the climate was constantly cooling throughout the Holocene~~over the whole Holocene with no early Holocene warming~~ due to the decreasing insolation forcing and atmospheric circulation variability. In contrast, N Canada experienced a strong warming with an overall warming rate over ~~up to~~ 1.~~4~~ °C ka-1 and this warming lasted untill~~till about~~ 7 ka~~ due to tremendous scale of the LIS and thus the dramatic influence on climate~~. Although i~~I~~n NW Europe, Arctic and Siberia different mechanisms played a role, the overall warming was similar in these regions, with a rate of around 0.5°C ka-1.~~, the overall warming were intermediate with a rate of about 0.5 °C ka-1, in spite of diverse mechanisms over different areas, as discussed above.~~ In addition, the comparison of early Holocene temperatures over NW Europe with proxy records suggest that the OGIS_FWF-v2 represented a more realistic climate condition than the OGIS_FWF-v1 did, and imply that the uncertainties with regard to the ice-sheet decay can be constrained by applying different deglaciation scenarios. ~~in the Arctic and NW Europe, the early Holocene temperatures were sensitive to meltwater flux from GIS, and a comparison with proxy records supports a relatively fast GIS thinning scenario.~~ Overall, our results demonstrated a large spatial variability in the climate response to diverse forcings and feedbacks, both ~~in~~ for early Holocene temperature distribution ~~terms of temperature distribution at the onset of the Holocene~~ and ~~in~~ for the early Holocene warming.

Acknowledgements

This work is funded by the China Scholarship Council. We would like thank Didier Roche for helping us to set up the experiments. The constructive comments of two anonymous reviewers and the editor are gratefully acknowledged.

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Table 1. Boundary conditions for 11.5 ka and pre-industrial (PI)

	11.5 ka			PI [a]		
Greenhouse gases (GHG)	CO_2 253 ppm	CH_4 511 ppb	N_2O 245 ppb	CO_2 280 ppm	CH_4 760 ppb	N_2O 270 ppb
Orbital parameters (ORB)	ecc 0.019572	obl 24.179 °	lon of perih 270.209 °	ecc 0.016724	obl 23.446 °	lon of perih 102.040 °
Ice sheets (relative to present)	Size $69.2*10^5$ km^2	Max thickness 2331 m	Meltwater flux 220 mSv	–	–	–

PI[a]: GHG for 1750 AD; ORB for 1950 AD.

Table 2. Experiments and corresponding setup

Equilibrium		Transient	
Name	Forcing	Name	Forcing
OG11.5	ORB+GHG	OG	ORB+GHG
OGIS11.5	ORB+GHG+IS+FWF	OGIS_FWF_v1	ORB+GHG+IS+FWF_v1
		OGIS_FWF_v2	ORB+GHG+IS+FWF_v2

Figure captions

Fig. 1. Evolution of greenhouse gas concentrations (GHG) shown as the radiative forcing's deviation from the pre-industrial level (with solid lines corresponding to the left axis), and June insolation at 65 °N derived from orbital configuration (with red line and the axis on the right).

~~Fig. 2. Monthly insolation anomaly (W m^{-2}) at 11.5 ka compared to present derived from Berger 1978.~~

Fig. 2~~3~~. The prescribed ~~ice~~ ice-sheet forcing during the early Holocene. (a) Variation ~~of size of~~in ice sheet extent~~s~~ (km^2) displayed as the black lines with the axis on the left and their maximum thickness (m) indicated by the green lines with the axis on the right. A relatively minor change in GIS is not shown due to its small scale~~;~~. (b) ~~and (c) denote~~ Two ~~the~~ freshwater flux ~~for the simulation~~scenarios (in mSv), FWF-v1 (dashed lines) and FWF-v2 (solid lines)~~ respectively~~. (c) Total meltwater discharge in equivalent sea level (m).

Fig. 3~~4~~. Simulated temperatures for 11.5 ka, shown as deviation from the PI~~ reference~~. Left column shows the simulation with only GHG and ORB forcings (OG11.5). For the right column, the ~~ice~~ ice-sheet forcing is included (OGIS11.5). Upper, middle and lower panels ~~are~~ present summer, winter and annual mean temperatures, respectively.

Fig. 4~~5~~. Simulated temperature evolution, shown as the anomalies compared to the PI, since the early Holocene at~~in~~ high latitudes (North of 70°). The ~~R~~red line indicates the simulation with only ORB and GHG forcings (ORBGHG), and~~.~~ the ~~B~~black and green ~~Green~~ lines represent the simulations OGIS_FWF-v1 and OGIS_FWF-v2, in which the ice sheets are included. (a), (b) and (c) panels represent the summer, winter and annual values respectively. The slope indicates the overall warming rate and is based on the least squares regression over the period from the 11.5 to 6 ka, as from 6 ka the temperature start to decrease. It is only a general estimation, thus uncertainty ranges are not provided. The warmest peak, is marked by shaded bar and is the simulated peak during which the temperature was over 1°C higher than in PI.

Fig. 5~~6~~. Simulated temperatures, shown as the anomalies compared to the PI, during the Holocene in Northwestern Europe (5 °W–34 °E, 58 °N–69 °N). The caption is the same as in fig. 4~~5~~.

Fig. 6~~7~~. Simulated temperatures, shown as the anomalies compared to the PI, during the Holocene in Northern Canada (120 °W–55 °W, 50 °N–69 °N). The caption is the same as in fig. ~~5~~4.

Fig. 7~~8~~. Simulated temperatures, shown as the anomalies compared to the PI, during the Holocene in Alaska (170 °W–120°W, 58 °N–74 °N). The caption is the same as in fig. ~~5~~4.

Fig. 8~~9~~. Simulated temperatures, shown as the anomalies compared to the PI, since the early Holocene in Siberia (62–145° E, 58–74 °N). The caption is the same as in fig. ~~5~~4,~~.~~ except that the warming rate slope is indicated for a shorter period.

Fig. 9. Model-data comparison over the latitudinal band of 30-90 °N, shown as a deviation from the PI. Black lines represent the stacked temperature reconstruction with 1δ uncertainty (grey band). Red and green lines indicate the simulated summer and annual temperatures.

Fig. 10. Summer surface albedo in the extratropical Northern Hemisphere. (a), (b) and (c) represent the control run (PI), the simulations without ice sheets (OG11.5) and with ice sheets (OGIS11.5) respectively.

Fig. 11. Geopotential height (m) at 800 hPa in the extratropical Northern Hemisphere. (a) shows the control condition PI, (b) and (c) are the simulations OG11.5 and OGIS11.5.

Fig. 12. Meridional overturning streamfunction (Sv) in the Atlantic Ocean Basin. (a), (b) and (c) indicate the control run (PI), the simulation OG11.5 and OGIS11.5 respectively. On the left hand side, depth is indicated in meters. Positive values indicate clockwise circulation.

Fig. 13. Minimum ~~sea~~ sea-ice thickness (m) in September for PI (a), OG11.5 (b) and OGIS11.5 (c).

~~Fig. 14. Simulated temperatures for 10 ka (shown as the deviation of 100 yrs average from PI). Left, middle and right columns show the simulation ORBGHG, OGIS_FWF-v1 and OGIS_FWF-v2 respectively. Upper, middle and lower panel indicate summer, winter and annual temperatures.~~

Fig. 14~~15~~. Response of the ocean variables (shown as a 100 yrs average) to forcings during the Holocene. (a) Maximum meridional overturning streamfunction (Sv) in the North Atlantic. (b) Sea ice area (10^{12} m^{2}) in the Northern Hemisphere. ~~Red~~ The red line indicates the ORBGHG simulation. The ~~B~~black and green lines reflect results of the simulation OGIS_FWF-v1 and OGIS_FWF-v2.

~~Fig. 16. Simulated winter surface albedo shown as a 100 yrs average in the extratropical Northern Hemisphere. (a) is for the PI. (b), (c) and (d) represent the simulations ORBGHG, OGIS_FWF-v1 and OGIS_FWF-v2 at 10 ka respectively.~~

Fig. S1. Monthly insolation anomaly (W m^{-2}) at 11.5 ka compared to the present-day derived from Berger 1978.

Fig. S2. Selected region denoted by the box over where the temperature evolution is shown.

Fig. S3. Simulated temperatures for 10 ka (shown as the deviation of 100 yrs average from PI).

Left, middle and right columns show the simulations ORBGHG, OGIS_FWF-v1 and OGIS_FWF-v2 respectively. Upper, middle and lower panel indicate summer, winter and annual temperatures, respectively

Fig. S4. Simulated winter surface albedo shown as a 100 yrs average in the extratropical Northern Hemisphere. (a) is for the PI. (b), (c) and (d) represent the simulations ORBGHG, OGIS_FWF-v1 and OGIS_FWF-v2 at 10 ka, respectively.